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About the Possibilities of Using an Air Mass Transformation Model in Taiyuan, Shanxi Province, China

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Contents

Abstract

The AMT-model is tested for trajectories arriving in Taiyuan to study the possibilities of using it in Taiyuan, People 's Republic of China. The sensitivity of the model for the different processes was studied. Some parameters of the model were modified for the purpose of forecasting in specific mountainous terrain and dry climate conditions. Results of examples which we have worked out for Taiyuan circumstances for the periods of July (summer) 1985 and January (winter) 1986, show that the 12 hour runs of the AMT-model are able to reproduce (on historical data) the sounding of Taiyuan. The AMT-model contribute fruitfully to short-range weather forecasts (12-36 hours ahead) during periods of severe air pollution and when cold waves occur.

1. Introduction

During the early eighties an Air Mass Transformation (AMT) Model was developed at the Royal Netherlands Meteorological Institute (KNMI). (J. Reiff et al.,1984), mainly for operational weather forecasting purposes (Blaauboer et al., 1987), but the model was also used to tackle problems in air pollution research (J.Reiff et al., 1988) and some problems in synoptic meteorology (Martin et al.,1988).

The AMT-model is meant to forecast (study) the potential temperature (θ), the specific humidity (q), and the depth (h) of the boundary layer at a specific position and a specific time of the day. It consists of a trajectory part, which describes the routes the air will follow from a source area to our point of interest and of an one-dimensional boundary layer model, which keeps track of the changes in the atmospheric boundary layer (ABL) alongthe lowest trajectory. In the source area initial temperature and humidity profiles are constructed from data of nearby radio soundings. These profiles are defined by a set of significant points, showing the inflection points of the profiles. This is done for trajectories which end at Taiyuan at the surface, 850, 700 and 500 hPa (only the u and v components of the wind are used).

For the boundary layer part of the model a mixed layer approach is taken, which assume mixed potential temperature (θ) and specific humidity (q) profiles during unstable (day) situations, and a linear mixed θ- and q-profile during stable (night) situations. See Figure 1.

During the movement of the air from the source area to our point of interest the model keeps track of the surface fluxes, i.e. the sensible heat flux H and latent heat flux LE and of the entrainment over the top of the ABL. The time-evolution of the average θ and q of the boundary layer and the boundary layer height are governed by the following equations:

$$\frac{d\theta_m}{dt} = - \frac{\overline{\theta_o{}'\omega_o{}'} + \omega_e\Delta\theta}{h} \tag{1}$$

$$\frac{dq_m}{dt} = - \frac{\overline{\theta_o{}'\omega_o{}'} + \omega_e\Delta q}{h} \tag{2}$$

$$\frac{dh}{dt} = - \frac{\overline{q_o{}'w_o{}'} + \omega_e\Delta q}{h} \tag{3}$$

in which

$$\overline{\theta_o{}'\omega_o{}'} = - \frac{g}{Cp} H \tag{4}$$

$$\overline{q_o'w_o'} = -gE \tag{5}$$

$$h = Ps - P_1 \tag{6}$$

$$\omega_e = \frac{c\overline{\theta_v'\omega_o'} - Au_*^3 g T_s \rho^2/h}{\Delta\theta_v} \tag{7}$$

$$\overline{\theta_v'\omega_o'} = \overline{\theta_o'\omega_o'} + 0.61\ T_s\ \overline{q_o'\omega_o'} \tag{8}$$

θ and q represent the jumps in the θ- and q-profiles at the top of the ABL. ω_1 and ω_0 are the large-scale vertical velocities at p_1 and p_s, respectively, which follow from the trajectory part of our model

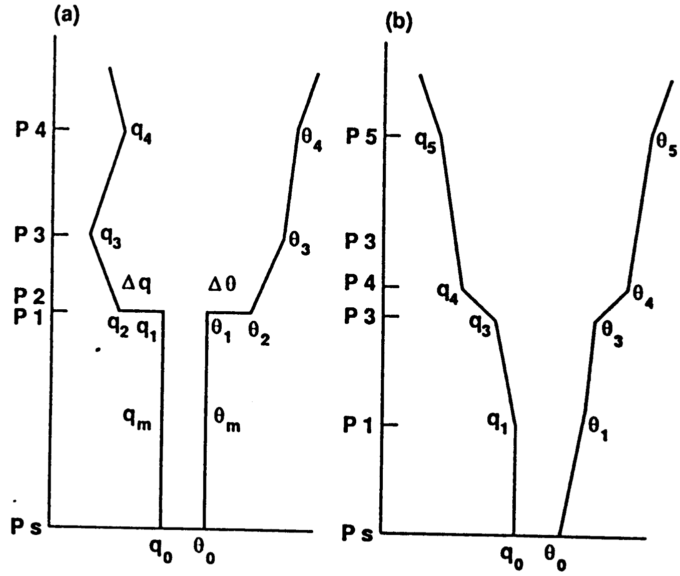

Fig. 1. Schematic diagram of the θ- anf q-profiles as used in the AMT-model. (a)=unstable case, (b)=stable case

The purpose of this article is to investigate the possibilities of applying the AMT-model for the conditions at Taiyuan, Shanxi province, in the centre of China.
To investigate this, a personal computer version of the AMT-model has been run for some cases (on historical data) of July (summer) 1985, January (winter) 1986, and the sensitivity of the model was tested for a number of variations in model parameters, that may play a role in the typical climate and geographical conditions around Taiyuan. Results of these tests are presented in section 3. From the results of these tests we know in which cases the AMT-model may help in forecasting the weather in Taiyuan.

2. Short survey of the climate of Taiyuan, Shanxi

Shanxi (Western mountains) province, as an inland province, is situated in the middle reaches of the Yellow River. Its area consists of about 156,000 square kilometer. It has a varied topography, mountainous terrain covering 72% of the province. Most of the area is higher than 1000 m above sea level.

Taiyuan city (37°47'N, 112°33'E), which has about 2 million inhabitants is situated in the centre of Shanxi at a bend of the Fen river (see Fig. 2). It lies 800 m above sea level in a valley, east of a S-N situated mountain-ridge. This ridge, the LuLiang mountains,with an average height of 1500 m from north to south, is about 300 km long. N-E of Taiyuan 100 km away, the Wu Tai mountain-ridge, with an average height of 2500 m, is situated, while East of Taiyuan, there is a ridge with an average height of 1800m.

Fig. 2. Sketch map of the People's Republic of China. The marked area is Shanxi province.

Shanxi and Taiyuan have a continental climate. The climate is also influenced by a monsoon circulation and by the specific geography. Annual mean rainfall is about 400-650 mm, annual global radiation, 120-140kc/cm^2, insolation duration is about 2200-3000 hours.

The climate of Taiyuan consists of a diurnal mountain-valley circulation (which may last for 5-10 days, interrupted by the passing of frontal systems which mainly pass from a westerly direction). The valley is approximately 15-20 km wide. Its air is, due to chimneys of the heatings of households (charcoal) and many industrial plants, heavily polluted.

The local circulation in Taiyuan is typically a mountain-valley wind circulation. In the morning, between 9 and 11 am local time, mountain breezes are predominical: the surface winds are from the north, while the upper wind, at approximately 500m, is from the south. Between 11 am and 13 pm local time the wind decreases to nearly wind-still conditions. Between 2 and 5 pm local time, the cell changes sign, surface winds from the south or valley winds prevail,while the 500 m winds come from the north. However, the strength of the winds in the afternoon cell is considerably weaker than in the morning cell, probably due to the mixing of horizontal momentum from turbulence caused by the increase in ABL-height. Between 7 and 9 pm local time the winds vanish again to nearly zero. Between 10 pm and 8 am local time there are little winds coming from the north. Most of the time the local circulation is strongest during winter. A radiation inversion occurs almost daily in the morning during the late days of autumn and winter, and the early days of spring. These are also the conditions in which the heaviest air pollution episodes take place.

In winter, from November until March, three or four times a month, weather systems pass. After these cold waves, bringing severe cold weather from northwesterly direction, with air that originates in Siberia. This air can also sometimes bring some snow and this precipitation makes up 2-3% of the annual precipitation. The temperature may dip 10 degrees Celsius below zero.

In spring, which lasts from April until May, more weather systems pass. These systems often move from west to east and maybe accompanied with strong winds. Sometimes these systems bring a little rain. In summer, June until August, not so many weather systems pass anymore. However, due to deep convection, in which the mountains play an important role, heavy rain and showers may develop. This contributes up to 60% of the annual precipitation. Daily mean temperature is about 22^{o}C. Sometimes the maximum temperature reaches 39^{o}C. In autumn, from September until October, slowly moving weather systems from the northwest often bring sometimes continuous rain with strong winds.

In general, the most striking weather events are: air pollution periods (most severe in winter), strong winds (most severe in spring), heavy rain or hail (in summer) and the sudden occurrence of cold waves (in late autumn). The winds inside the valley in Taiyuan are often different from the winds aloft and the winds outside the valley.

3 An experiment with the AMT-model in Taiyuan

3.1 The calculation of trajectories and the influence of the amount of air that overflows the mountains.

In The Netherlands, the trajectories were calculated by means of geostrophic winds taken from the analyses of the ECMWF-model. Wind data are available every two hours in The Netherlands, but only every twelve hours in Taiyuan. So the wind data put in the AMT-model, are obtained by linear interpolation from every twelve hours to two hours. Maybe it has little influence for the higher level trajectories but it has a considerable influence for the lower level trajectories, because it does not consider the influence of orography, friction, daily variation of surface wind and meso-scale and micro-scale weather systems etc. To solve this problem, and to get data of wind fields for shorter time steps, we also need to take appropriate modifications for some parts of the model on the basis of local climatic characteristics, geographic environment and experience of the forecaster etc.

Not all the air that reaches the mountain ridge from the West will be lifted and flow over the mountain into the valley of Taiyuan. Normally a part will be lifted and a part of the air will flow alongside the mountain ridge, see Figure 3. More stable air (more stratified), will be lifted more difficultly, therefore the stability of the air-column plays a role in how much of the air will be flow over the mountain ridge and how much of the air will circumvent it

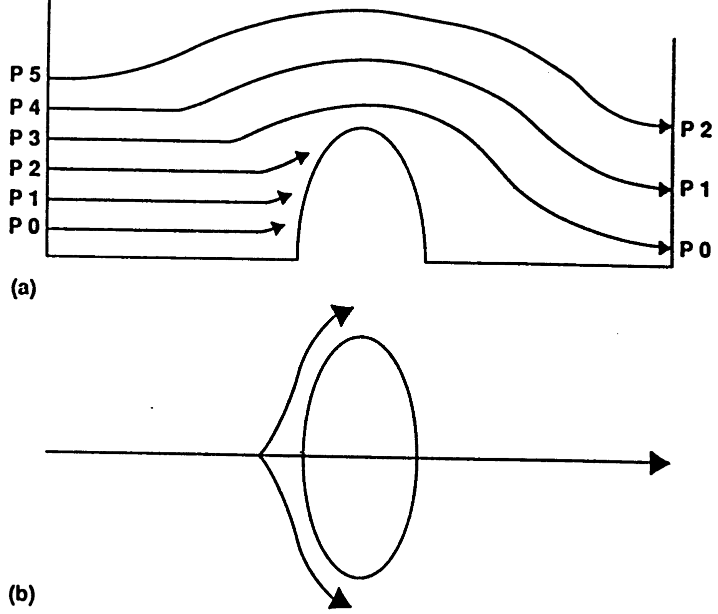

Fig. 3. The pattern of the air mass that overflows a mountain

To find out how much of the air was lifted on 3 January 1986 four runs were made with the AMT-model. Each result was compared with the observed radio sounding of Taiyuan, to find out which result resembles the observed sounding closest.

To test the correctness of this assumption, four runs were made with the data of 8 am and 8 pm local time on 3 January, 1986. First we calculated the trajectories of 1000, 850, 700, 500 hPa. The result is shown in Fig. 4.

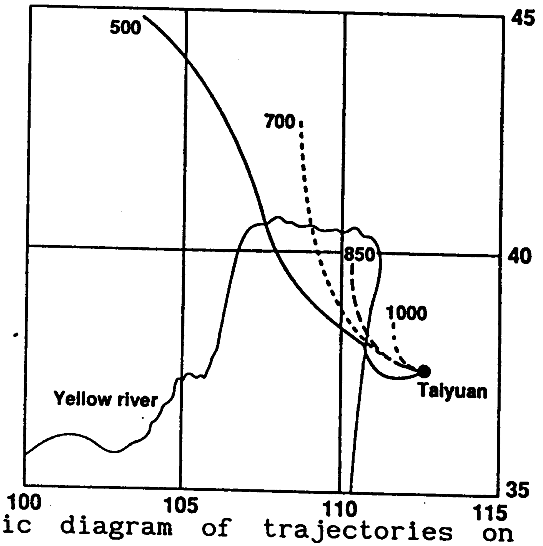

Fig. 4. Schematic diagram of trajectories on 3 January 1986 between 8.00 am and 8.00 pm local time.

There are four runs made, to decide which part of the air-column that moves towards the mountain will actually overflow the mountain:

(1) Only the air at the same level and higher than the mountain is assumed to overflow the mountains (the lowest point 853 hPa). In this case the air mass is going down to 85 hPa on its way to Taiyuan.

(2) Some air is lifted first, then going down. Choose 865 hPa instead of 853 hPa.

(3) It is assumed that air lower than 880 hPa flows along the mountain foot, while air above that height is first lifted to move over the ridge and then sink into the valley of Taiyuan.

(4) All of the air from the source area flows over the LuLiang mountains (above sea level 1500 m). The surface pressure in the source area is about 912 hPa. The surface pressure in Taiyuan is 938 hPa. In this case the air mass drops 26 hPa.

The results of the runs are given in table 1.

Table 1: Example of the influence of different amounts of air that climb over a mountain for temperature (T), relative humidity (f) and boundary layer height (h)

P(hPa)	T(°C)	f(%)	h(m)
853	-7.8	26.2	613
865	-8.4	27.5	582
880	-8.9	28.3	549
912	-11.1	34.8	475

The observed temperature at that time is -8.3°C, relative humidity is 20%, but there is not a value of h. Because the observed value of relative humidity is less reliable than temperature, the conclusion of the following is mainly dependent on temperature. From table 1 it can be seen that the value of 865 hPa gives more satisfactory results. For the height of the mountain, about 1500 m in this case, the conclusion is in accordance with the assumption about an air mass overflowing a mountain. In this case 20% of the air in front of the mountain was lifted over the mountain and 80% of the air streamed alongside the mountain.

It must be stressed, however, that the value of 865 hPa is strictly speaking only valid for this case. As the stability of the arriving air plays a role, more experiments, also experiments in which the air passes at other points (so at other heights) the mountain ridge, are necessary.

3.2 The influence of the surface humidity

For the description of the vertical surface flux of sensible heat (H) and the vertical surface flux of moisture (LE), $\beta 1$ (a parameter that accounts for the soil moisture) is required (J. Reiff et al, 1984). The value of $\beta 1$ that was used in The Netherlands is typical for the wet climate in western Europe, $\beta 1$ is equal to one. The climate of Shanxi province, however, is a continental climate, so the value of $\beta 1$ has to be changed. Results of earlier studies in Shanxi province (not published) suggests that the mean value of $\beta 1$ is 0.10-0.25.

To determine the sensitivity of model results for $\beta 1$ and to determine the best value, we have investigated the following cases:

(1) $\beta 1=0.5$, not completely wet surface.
(2) $\beta 1=0.25$, normal surface.
(3) $\beta 1=0.18$, not completely dry surface.
(4) $\beta 1=0.11$, dry surface.

We have made some runs in winter, summer and varied situations of weather for the comparison of different model results. We have taken 4.00 pm local time in summer and 2.00 pm local time in winter as time of arrival. About this time the maximum temperature at Taiyuan occurs and the ABL-height tends to stabilize. The results are given in table 2 and table 3.

Table 2: The model results of different $\beta 1$ in summer (4.00 pm local time)

$\beta 1$	T(°C)	f(%)	h(m)
0.11	31.4	34	1850
0.18	31.2	35	1784
0.25	30.8	37	1700
0.50	29.5	43	1427
obs value*	30.6	60	

Table 3: The model results of different $\beta 1$ in winter (2.00 pm local time)

$\beta 1$	T(°C)	f(%)	h(m)
0.11	-9.14	18.8	787
0.18	-9.21	19.9	774
0.25	-9.29	21.6	765
0.50	-9.89	26.0	721
obs value*	-9.0	21	

* = The observed values are the mean of the values at the stations which are near the air mass at that time.

Table 2 and table 3 show, that a good knowledge of the surface humidity is important. However, values of $\beta1$ below 0.25 do not change the result very much.

From these model results and from the studies made earlier, we decided to take $\beta1=0.25$ as the most reliable value in summer and take $\beta1=0.11$ in winter. However, it must be stressed that when it has rained during the last days over a considerable stretch that the surface trajectory pass, a higher value must be taken.

3.3 The influence of the choice of the lowest trajectory

As the winds at different heights have different speeds and directions, the origin of the different trajectories will, in general, not be same (see Fig 4). The designers of the AMT-model assume, however, that the ABL is advected with the lowest trajectory. As a consequence, the trajectory of a significant point just above the ABL is terminated when the increasing ABL meets this significant point. From that time onward, the position of the air it represents, is described by the ABL trajectory. We try to investigate this assumption in Taiyuan. Let us see the following observed facts.

On the basis of observations of the ABL at Taiyuan area (Zhang Huaide,Gao Kang et al, 1984), the average maximum depth of the ABL in summer can reach to 2500-3000 m in non-cloudy cases and is often between 1500-2000 m in cloudy cases. Taiyuan is situated 800 m above sea level. This means that the level of which the transport of the average ABL during day time takes place, is about 700-1000 m above the surface (during nighttime this is 50-200 m). In Taiyuan circumstances this means that the 850 hPa wind can, during daytime in summer, best be taken as the ABL transport wind.

However, the surface pressures of the lowest trajectories at initial starting point in our examples were much lower than 850 hPa. The lowest trajectories which govern the transport of the ABL were interpolated between the 1000 hPa and 925 hPa trajectory or between the 925 hPa and the 850 hPa trajectory. In order to test the sensitivity of the model for a changing surface trajectory, 3 cases were calculated:

(1) The 925 hPa wind the same as the 1000 hPa wind, the 850 hPa wind no change.
(2) The 925 hPa wind is interpolated between the 1000 hPa and the 850 hPa wind.
(3) For the 1000 hPa and 925 hPa winds, the 850 hPa wind is taken.

The results of these cases are shown in table 4.

Table 4: The influence of different lowest trajectories for model results in summer

run (n)	T(^{o}C)	f(%)	h(m)
run (1)	30.93	36.2	1737
run (2)	30.80	36.7	1704
run (3)	30.82	37.4	1648

From table 4 it is seen that the result trajectory does not differ very much. But if there is much difference between the surface wind and 850 hPa wind and at the same time there is much difference in the distribution of weather elements of horizontal gradient and vertical gradient as well, the difference in the resulting soundings may be much larger accordingly. We then must take care to use the best transport level for the surface trajectory. However, these cases not often happen in summer in Taiyuan.

Because of the lower height of ABL and the smaller difference between the lowest trajectory and mean transport level (leading advection) of ABL during nighttime in summer, the difference in the resulting soundings must also be much smaller. Most of the cases, as has been indicated above, assume that the ABL as a whole is advected with the lowest trajectory, which was proved to be correct in Taiyuan area.

3.4 The influence of the cloud amount along the lowest trajectory

Above land the cloud amount plays an important role in the surface flux. The development of cloud amount is largely determined by net radiation fluxes. It is rather sensitive to the forecast of such fluxes. The AMT-model needs the cloud amount along the trajectory of the ABL. In the flux calculation, the predicted cloud amount in the free atmosphere of the European Centre's model (Reiff and Blaauboer,1982) was employed by the KNMI. We have to replace that by other methods.

To investigate the sensitivity of the cloud amount for the model results, we choose one example which takes a series of different parameters N from 0, 1, 2, 3, 4, 5, 6, 7 to 8 octas, respectively. The change process of the temperature, relative humidity and the depth of ABL at Taiyuan at 4.00 pm local time are shown in Fig.5.

(1) With the increase of cloud amount at first, the temperature (T) and depth (h) of the ABL tends to increase, beyond N=4, (T), (h) tend to decrease with increasing N.The extreme value of three variables occurred when N=3 to 4.

(2) When the cloud amount is N=0, 1, 2, 3, 4, 5, respectively, the model results are considerably less dependent on the cloud amount. However, when N>5, the variables changed rapidly. So, good forecasts of the cloud amount along the lowest trajectory are very important for the model results.

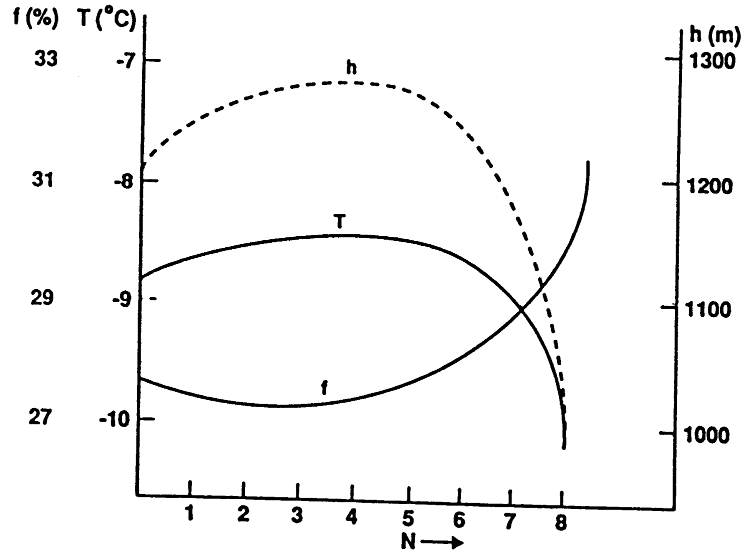

Fig. 5. Schematic diagram of the influence of the cloud amount for the model results

Because historical data are used for all the experiments, we have obtained the data of cloud amounts by reading weather charts of surface. In future applications, weather satellite cloud pictures and synoptic analysis will be used.

3.5 The influence of vertical advection

To test the influence of the large-scale vertical velocity, four cases were investigated:

(1) Downward vertical velocity (at 500 hPa, 50 hPa/12 hours; at 700 hPa, 30 hPa/12 hours; at 850 hPa, 15 hPa/12 hours; at 925 hPa, 7.5 hPa/12 hours; at 1000 hPa, 0 hPa/12 hours).
(2) No vertical velocities.
(3) The same as (1), but upward.
(4) The same as (3), but two times larger.

The results of this experiment on the influence upon the potential temperature, specific humidity and boundary layer depth at the surface level and at the 600 hPa level are given in table 5.

Table 5: The influence of the vertical advection

case (n)	$\theta 0$(°C)	$\theta 600$(°C)	f0(%)	f600(%)	h(m)
case (1)	32.4	5.5	32.5	37	1881
case (2)	32.2	3.4	33.3	57	2021
case (3)	31.9	1.2	33.9	73	2182
case (4)	31.7	-0.1	34.5	90	2358

Table 5 shows, that changing the large-scale vertical velocity has a slight influence upon the surface temperature. However, we must be careful. The relative humidity at the higher levels of the computed soundings changed from 73% (case 3) at the 600 hPa into 90% (case 4). As it is difficult to guess large scale vertical velocities, without the results of grid point numerical weather, some values based on our experience were taken. At the present stage of the model we could not get satisfactory large-scale vertical velocities. Therefore the development of ABL clouds cannot be predicted satisfactorily.

3.6 Modification of some parameters in the original AMT-model

1) Replacement of geostrophic wind data by observed wind data. We have used observed wind fields for the lowest trajectory calculations instead of the geostrophic wind, used in the original model. Due to the existence of large differences between the observed wind speed and geostrophic wind speed, some problems (such as friction velocity, parameterization of the surface fluxes at nighttime and so on) will occur. We modified some parameters of the original program of the AMT-model.

2) In the AMT-model H is going through zero 30 minutes before sunset, and LE is positive still after sunset, as is measured in circumstances in NW-Europe (the evaporation of leaves goes on beyond sunset). To test this in Shanxi circumstances, the parameter that governs this, is changed over the range 0, 15 minutes and 60 minutes respectively. Results are shown in tables 6 and 7.

Table 6: Results at 8.00 pm local time in summer

parameter	T (^{o}C)	f (%)	h (m)
0	31.0	35.6	31
15	30.8	36.1	33
30	30.7	36.6	33
60	30.3	38.0	32

Table 7: Results at 8.00 pm local time in winter

parameter	T (^{o}C)	f (%)	h (m)
0	-13.01	24.6	193
15	-12.89	24.9	193
30	-12.63	25.6	193
60	-12.37	26.1	193

From table 6, we can see that in summer the parameter 30 did not have much effect on the calculated results of the model. So we took the parameter the same as the value of the original model. (H goes through zero 30 minutes before sunset)

From table 7, we can see that in winter with the decrease of solar altitude angle, this parameter doesn't also have much effect on the results. Because less evaporation occurres in winter and therefore we expect less shifts in H and LE, the parameter is taken 15.

3.7 Description of the predicted profiles

The cases we worked out for Taiyuan conditions (July 1985 and Jan. 1986) show that, at least for these cases the AMT-model is able to reproduce the sounding of Taiyuan in a 12-hours forecast. Fig. 6 is an example of the sounding as used in the ABL model at 12.00 (GMT) 3 January, 1986.
It illustrates that the model temperature "profile" approximates the observed values, but the assumption of mixed moisture in the ABL during unstable situation is not satisfactory.

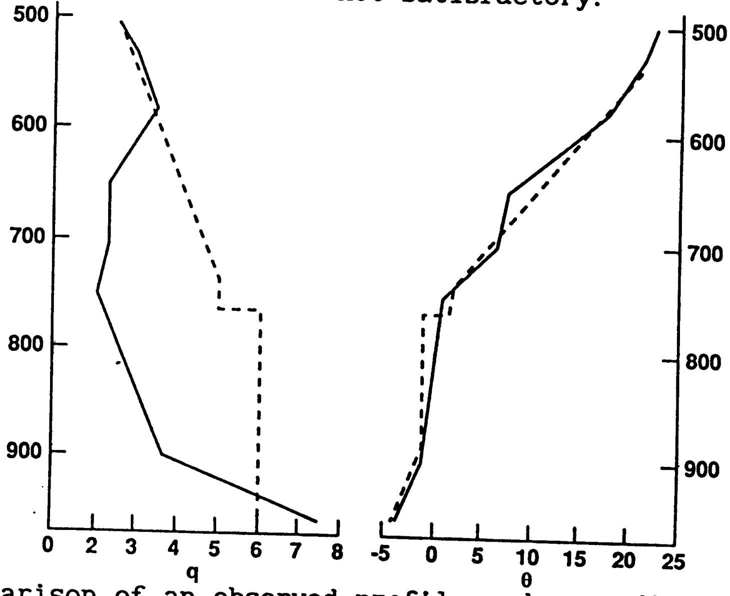

Fig. 6. Comparison of an observed profile and a predicted profile at Taiyuan (8.00 pm local time) on 3 January 1986. The dashed lines give the predicted profiles, The thick solid lines refer to the radiosounding profile. The profiles are given in a p,θ,q system.

The moisture profile is not well presented by the model. It is probably caused by four reasons:

1) β1 is too small
2) Advection at 850, 700 hPa comes from another region with drier air
3) Vertical velocity (downward) is stronger.
4) H+LE is less than calculated, β1 is too high (alfa is too low maybe).

4 Conclusions

From our investigations the following conclusions can be drawn:

(1) When the AMT-model is used in a mountainous area, it is necessary to modify the model according to the pattern of air mass overflowing over mountains, to eliminate the influence of mountainous areas.

(2) It is clear that in other climates the values of some parameters must be changed. The values of the parameters that were used in The Netherlands are typical for the wet climate in Western Europe in a flat country while the circumstances of the climate and terrain in Shanxi are quite different from those in The Netherlands.

(3) The density of spatial and temporal distribution and the precision of information used must meet certain requirements.

In general, from our investigations we found that in the Taiyuan circumstances the AMT-model proved to be valuable in forecasting the temperature and the height of the ABL in summer and in winter. The examples we worked out for the Taiyuan circumstances show that the AMT-model is able to reproduce (on historical data) the sounding of Taiyuan in a 12-hours forecast.

This and a careful examination of the local Taiyuan climate makes us believe that the AMT-model may fruitfully contribute to the short range weather forecast (12-36 hours ahead) during periods of severe air pollution and when cold waves occur. Before the model can be applied during these circumstances, however, still many tests on historical data sets are necessary.

5. Acknowledgements

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